Final Report for Period: 04/2006 - 03/2007
Submitted on: 05/15/2007
Principal Investigator: Melkote, Shreyes N.
Award ID: 0300457
Organization: GA Tech Res Corp - GIT
Title:
Modeling of Size-Effect in Micro-Cutting Process Using Strain Gradient Plasticity

Project Participants

Senior Personnel

Name: Melkote, Shreyes
Worked for more than 160 Hours: Yes
Contribution to Project:

Post-doc

Graduate Student

Name: Subbiah, Sathyan
Worked for more than 160 Hours: Yes
Contribution to Project:
Doctoral candidate working as a graduate research assistant on the project. Looking at both experimental and analytical modeling approaches to explain size-effect in micro-cutting based on analysis of the cutting forces.

Name: Liu, Kai
Worked for more than 160 Hours: Yes
Contribution to Project:
Doctoral candidate working as a graduate research assistant on the project. Working on numerical modeling of the orthogonal micro-cutting process incorporating a non-local law of strain gradient plasticity. Is currently supported on another NSF grant that ends on 03/31/04. Is extending the numerical model developed in that grant to the current project.

Name: Ng, Chee Keong
Worked for more than 160 Hours: Yes
Contribution to Project:
Masters thesis candidate working as a graduate research assistant on the project. Will carry out the experimental work on micro-cutting of ferrous and non-ferrous materials at the National University of Singapore and at Georgia Tech.

Name: Han, Sangil
Worked for more than 160 Hours: Yes
Contribution to Project:
Mr. Han assisted for 5 months in experimental aspects of the micro hard turning work.

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Name: Penny, Issac
Worked for more than 160 Hours: Yes
Contribution to Project:

The student was hired in the Fall semester of 2004 and received training in the use of laboratory equipment such as the Hardinge Superprecision CNC Lathe, force data collection, hardness measurement, and general machine shop training. The student was funded through the NSF REU Program.

Years of schooling completed: Junior
Home Institution: Same as Research Site
Home Institution if Other:
Home Institution Highest Degree Granted(in fields supported by NSF): Doctoral Degree
Fiscal year(s) REU Participant supported: 2005 2004
REU Funding: REU supplement

Name: Newton, Thomas
Worked for more than 160 Hours: Yes
Contribution to Project:
Mr. Newton was a NSF REU student who conducted micro turning experiments on hardened steel.

Years of schooling completed: Other
Home Institution: Same as Research Site
Home Institution if Other:
Home Institution Highest Degree Granted(in fields supported by NSF): Doctoral Degree
Fiscal year(s) REU Participant supported: 2006 2005
REU Funding: REU supplement

Name: Alberts, Matthew
Worked for more than 160 Hours: Yes
Contribution to Project:
Matthew worked with graduate student Ramesh Singh learning how to use a 2-axis micro-machining setup developed for laser-assisted mechanical micro-grooving. He also assisted Mr. Singh on conducting micro-cutting experiments.

Years of schooling completed: Junior
Home Institution: Same as Research Site
Home Institution if Other:
Home Institution Highest Degree Granted(in fields supported by NSF): Doctoral Degree
Fiscal year(s) REU Participant supported: 2007 2006
REU Funding: No Info

Name: Martinez, Jose
Worked for more than 160 Hours: No
Contribution to Project:
Jose Martinez also worked with Mr. Ramesh Singh on the 2-axis micro-machining setup. He assisted Mr. Singh in micro-grooving experiments designed to validate the mechanistic cutting force model for micro-cutting developed by Mr. Singh.

Organizational Partners

National University of Singapore

Faculty associated with the Advanced Manufacturing Lab in the Mechanical Engineering Dept. at NUS will be providing access to their micro-machining and metrology equipment for use by Georgia Tech researchers.

Other Collaborators or Contacts

Initial discussions on performing some micro-cutting tests on a ultra-precision machine tool have been held with Dr. Rob Ivester of NIST.

Quick stop micro cutting tests were conducted by Mr. Subbiah at IIT Bombay - India in December 2005.

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)
The goals of the proposed project are to explain the size-effect phenomenon in micro-cutting, and to develop a fundamental understanding of chip formation and surface integrity in micro-cutting of common engineering metals not investigated to date. These goals will be realized through a combination of analytical/numerical modeling and experimental efforts.

The specific objectives of the project were as follows:

1. Development of analytical/numerical models based on strain gradient plasticity for the 'size-effect' arising from the primary, secondary and tertiary deformation zones in orthogonal micro-cutting.

2. Verification of the 'size-effect' models through orthogonal micro-cutting experiments.

3. Experimental study of the effects of cutting conditions on chip formation and surface integrity in orthogonal micro-cutting process for common engineering ferrous and non-ferrous alloys.

The following were the major activities in this project since its inception in 2003:

1. Development and experimental validation of numerical (finite element) and analytical models of orthogonal micro-cutting to explain the size-effect commonly observed in the specific cutting energy. Specifically, the modeling effort focused on the following aspects of the problem:

ò A finite element model of orthogonal (plane-strain) micro-cutting that accounts for material strengthening due to strain gradient plasticity effects at the micron scale was developed. The model was developed using the ABAQUS/Standard (ver.6.3) software. In addition to accounting for strain gradient induced material strengthening, the model also considers the effect of material strengthening due to decrease in secondary shear zone temperatures with decrease in the uncut chip thickness and the effect of tool edge radius.

ò Experimental validation of the model under a range of micro-cutting conditions.

ò Detailed analysis of the relative contributions of strain gradient induced material strengthening, thermal 'hardening' and tool edge radius effects. This was accomplished through simulations conducted using the finite element model.

ò Development of finite element model of orthogonal micro-cutting to examine the role of material separation leading to chip formation due to ductile fracture in causing the size effect in specific cutting energy. This model was implemented in ABAQUS/Explicit (ver.6.3). Unlike the finite element model incorporating strain gradient plasticity effects, which relies on automatic remeshing to simulate chip formation and ignores material separation due to ductile fracture, this model makes use of an accumulated damage criterion based on a strain, strain-rate and temperature dependent fracture strain.

ò Experimental validation of the ductile fracture-based material separation model. Model validation experiments were performed for two ductile materials (OFHC Copper and Al2024-T3) and over a range of cutting speeds and uncut chip thickness values.

ò Detailed analysis of energy consumed in material separation and its contribution to the size-effect in specific cutting energy. The stress state ahead of the tool tip was analyzed to determine if the conditions generated in micro-cutting are conducive to ductile fracture. In addition, the effect of tool edge radius on material separation due to ductile fracture was also analyzed.

ò Development of a dislocation theory based analytical model to estimate the constant force component responsible for material separation due to ductile fracture in micro-cutting.

2. Modeling the influence of plastic side flow in micro-turning on the resultant surface roughness. This was accomplished by combining a material rheological factor that is a function of the material strength and is derived from an indentation-scratch model with kinematic surface roughness in turning.

3. Novel orthogonal micro-cutting experiments to isolate the constant force component responsible for material separation during chip formation. Both low speed and high speed micro-cutting tests were performed. Some of the high speed tests using a hammer-pin type

quick-stop device were carried out by the graduate student at IIT-Bombay in India.

4. Novel orthogonal micro-cutting tests to show experimental evidence of ductile fracture at the chip root. This evidence was obtained by viewing the instantaneous chip root in an SEM.

5. Experiments to understand the influence of tool edge radius on material separation due to ductile fracture.

6. Detailed experimental study of chip formation, cutting forces, and surface finish in microscale (up to 2 microns uncut chip thickness) and nanoscale (down to 10 nm uncut chip thickness) cutting of aluminum 7075-T6 and P20 mold steel. These tests were performed on a Toshiba Ultraprecision Machine Tool located in Department of Mechanical Engineering at the National University of Singapore.

7. Training a total of 4 Ph.D. students (Primary students: Dr. Kai Liu and Dr. Sathyan Subbiah; Partially supported students: Dr. Sangil Han and Mr. Ramesh Singh), 1 M.S. student (Mr. Chee Keong Ng), and 4 NSF REU students (Mr. Thomas Newton, Mr. Issac Penny, Mr. Matthew Alberts, and Mr. Jose Rafael Martinez). The REU students received hands-on training on various aspects of micro-cutting as they worked with the graduate students.

8. A couple of the graduate students, Dr. Sathyan Subbiah and Mr. Ramesh Singh, volunteered their time at inner city high schools to tutor students in mathematics.

9. Dissemination of research results through several technical presentations (at meetings, conferences) and seminars, and refereed and non-refereed publications in major manufacturing research conferences and leading technical journals (9 journal publications, 3 peer-reviewed conference publications, 1 non-refereed publication). See under 'Publications' and 'Presentations' sections of the attached report for more details.

Findings: (See PDF version submitted by PI at the end of the report)

The major research findings of this project in the following specific areas are summarized below: 1) Analysis of size-effect due to strain gradient, thermal and tool edge radius effects, 2) Analysis of size-effect due to material separation via ductile fracture, 3) Effect of plastic side flow on surface roughness in micro-turning, 4) Experimental investigation of micro-/nano- scale cutting of ferrous and non-ferrous engineering alloys, and 5) NSF REU project findings.

1. Analysis of size effect due to strain gradient, thermal and tool edge radius effects

ò The finite element model of orthogonal micro-cutting incorporating the effects of strain gradient plasticity and thermal softening/hardening was found to be capable of predicting the size effect in specific cutting energy over a range of uncut chip thicknesses (2-200 microns) and cutting speeds (1.2 û 240 m/min). The model predictions of the forces and specific cutting energy are in good agreement with measured values.

ò Strain gradient strengthening contributes significantly to the size-effect at low cutting speed (< 10 m/min) and small uncut chip thickness (< 10 microns).

ò Temperature dependence of flow stress is the dominant cause of size effect at high cutting speeds (> 200 m/min) and larger uncut chip thickness (> 20 microns). The size effect is caused by material strengthening due to drop in the secondary shear zone temperature.

ò Strain gradient strengthening is more dominant than the temperature effect at high cutting speed (> 200 m/min) and small uncut chip thickness (< 10 microns).

ò Tool edge radius accounts for only part of the size effect in micro cutting.

ò The contribution of edge radius to size effect arises from: (a) increase in size of plastic shear zone around the tool tip, and (b) higher frictional energy dissipation due to increased tool-chip contact length.

ò Under cutting conditions where the strain gradient effect is dominant the nonlinear increase in specific cutting energy occurs near the intrinsic material length scale l.

2. Analysis of size-effect due to material separation via ductile fracture

ò By viewing specific cutting energy as a ratio of two numbers the cause for the size effect is attributed to an increasing component of the cutting force and/or a constant force component.

ò Special experiments at high rake angles can serve to isolate the constant force component. Cutting force trends at high rake angles (up to 70 deg.) that minimize the shear in the chip indicate that the force tends to a constant value at higher rake angles approaching 90 deg.

ò SEM images of the chip-workpiece interface for OFHC copper and Al2024-T3 show clear evidence of ductile fracture ahead of the tool leading to chip formation.

ò Ductile fracture occurs in a narrow zone spanning the width of cut and directly in front of the cutting tool edge. These observations put to rest criticisms about the use of a pre-defined sacrificial layer in numerical simulations to model chip separation either by node release or element deletion. As long as physically-based fracture models or damage models pertaining to the nature of failure are used to release the nodes or delete elements, it is argued here that this approach is valid.

ò The crack extension force associated with ductile fracture is found to be comparable with the constant cutting force observed at high rake angles. With shear in the chip being minimal at such high rake angles, the mechanism of chip formation (material separation) is primarily ductile fracture or ductile tearing ahead of the tool.

ò The numerical model incorporating sacrificial layers and damage simulated by a J-C damage model was found to be in good agreement with the measured cutting and thrust forces (max. error < 9% and 15%, respectively) for micro-cutting of Al2024-T3.

ò The stress state ahead of the cutting tool shows that the pressure is positive closer to the cutting edge and negative further ahead. An element in the sacrificial layer changes its stress state to tensile as it approaches the cutting tool leading to ductile fracture.

ò Analysis of energy consumed in micro-cutting indicates that the percentage of energy consumed in plastic dissipation in the chip decreases with uncut chip thickness, while that of the sacrificial layer increases.

ò In absolute energy terms, the energy consumed in material separation is seen to not vary significantly as the uncut chip thickness is reduced. This appears to support the hypothesis that there is always a constant force component associated with cutting.

ò The size-effect in specific cutting energy is clearly observed in Al2024-T3. The specific energy associated with material separation is found to increase substantially with decrease in uncut chip thickness and plays an important role in explaining the scaling in the specific cutting energy.

ò The chip-workpiece junction consists of an interface zone of metal when cutting with an edge-radius tool. Such an interface is absent in the case of an up-sharp tool (with edge radius much smaller than the uncut chip thickness).

ò The interface zone of metal is found to fracture at three locations: one, at the upper edge closer to the chip, two, in the middle of the zone, and three, at the lower edge closer to the workpiece surface.

ò Based on observation, it is hypothesized that an element of metal approaching the edge-radius tool tip wraps around the edge and then is stretched in opposing directions: in the direction of the chip-flow and in the direction of workpiece surface movement. Depending on which area is weaker and how strong these stretching effects are the element of metal can fracture at the upper, middle and/or the lower edges of the interface zone.

ò The mean stresses in front of the tool are tensile even with an edge radius tool indicating favorable conditions for fracture to occur.

ò All stress components in front of the tool tip are consistently lower with the edge radius tool than the sharp tool indicating that a sharp tool provides a more favorable condition for fracture to occur.

ò A higher percentage of energy is spent in the sacrificial layer and the sub-surface in the case of the edge radius tool than the sharp tool.

3. Effect of plastic side flow on surface roughness in micro-turning

ò It is found that most of the discrepancy between the theoretical and measured surface roughness in micro-turning of Al5083-H116 alloy is largely due to the additional surface roughening caused by plastic side flow.

ò The increase in roughness with decrease in feed after reaching a minimum can be attributed to increased plastic side flow caused by the strain-gradient induced strengthening of the material directly ahead of the tool.

ò Significant improvement in roughness prediction is achieved using the developed surface roughness model. The percentage error of the prediction using the developed model is less than 15% for all feeds investigated.

4. Experimental investigation of micro-/nano- scale cutting of ferrous (P-20) and non-ferrous (Al7075-T6) engineering alloys. The key findings for Al7075-T6 are (Ng, et al., 2006):

ò Continuous chips are observed over the entire range of undeformed chip thicknesses (10 û 2000 nm) investigated.

ò The cutting force exhibits an approximately linear relationship with the undeformed chip thickness when cutting at undeformed chip thicknesses greater than the edge radius of the tool (60 ~ 100 nm).

ò When the undeformed chip thickness is smaller (10 û 60 nm) than the edge radius of the tool, a non-linear variation in the cutting forces is observed.

ò A size effect in the specific cutting energy is observed at undeformed chip thicknesses smaller (10 û 60 nm) than the edge radius of the tool.

ò The cutting speed has a negligible effect on the cutting force at undeformed chip thicknesses less than ~700nm.

ò The shear angle increases initially and then decreases as the undeformed chip thickness is increased.

ò The mean friction coefficient exhibits a size-effect that can be explained via material strengthening due to decrease in tool-chip interface temperature with decrease in undeformed chip thickness.

ò The machined surface at an undeformed chip thickness smaller than the edge radius of the tool (10 û 60 nm) is rougher than at larger undeformed chip thickness for both cutting speeds (10 m/min and 150 m/min).

5. NSF REU Project Findings:

ò Binderless cBN tools do not perform as well (in terms of tool wear) as high content cBN tools in interrupted micro-cutting of hardened steel at conventional cutting speeds (120 m/min). They tend to wear less than high content cBN tools at higher cutting speeds (180 m/min).

ò The effect of interruption length (used as a parameter to characterize the interruption geometry) on tool wear is more significant than the effect of interruption ratio.

ò Surface integrity (white layer formation) is better with a binderless cBN tool than with the high content cBN tool in interrupted micro-cutting of hardened steel.

ò The mechanistic orthogonal micro-cutting force model was found to be in good agreement with experimental results.

Training and Development:

Research skills and experience gained by graduate students and undergraduate research assistant include:

1. systematic steps to use in carrying out high quality research
2. hands-on experience in using precision and ultraprecision machine tools, metrology equipment and associated sensors for data acquisition.
3. analytical modeling using dislocation mechanics approach
4. advanced numerical modeling using the finite element approach for simulating the metal cutting process including strain gradient effects.
5. analysis modeling of micro-cutting using the mechanistic approach.

Teaching skills and experience gained by graduate students include:

1. giving presentations of work to industry visitors and other faculty.
2. ability to prepare a technical paper describing key results.

Research/teaching skills and experience gained by undergraduate students:

* The NSF REU students (Mr. Issac Penny and Mr. Tommy Newton)have been trained on the use of the Hardinge T42 Superprecision Lathe,

and the use of the microhardness tester. Mr. Alberts and Mr. Martinez received training in operating a 2-axis micro-grooving machine along with the use of thermocouples and cutting force measurement transducers.
* Mr. Newton has completed a detailed experimental investigation of tool wear and surface integrity in micro cutting of hardened steels and has learnt how to write a peer-reviewed technical paper.
* Mr. Newton has made presentation of his work to industry representatives.

Outreach Activities:
Outreach activities include:

1. Presentation of project results to date in the Lab-Fresh Session on Machining Processes Research at the ASME IMECE held in Washington, DC from Nov. 15-21, 2003.

2. Participation by one of the graduate students in tutoring (math) and mentoring largely-minority elementary school kids at an Atlanta area elementary and high schools through Georgia Tech's CEISMC program.

3. Poster presentations by students at the Industrial Advisory Board meeting of the Precision Machining Research Consortium at Georgia Tech in October 2003 and 2004, and in March 2006.

4. Poster presentation by graduate students at the 2004, 2005, and 2006 NSF Research Conferences and at the 2005 ICAMDD conference in Goa, India.

5. Paper presentations by graduate students at the 2004 Japan-USA Symposium on Flexible Automation (Kai Liu), the 2004 ASME IMECE in Anaheim, CA (Sathyan Subbiah), the 2005 ASME IMECE in Orlando, FL (Kai Liu and Sathyan Subbiah), 2006 NAMRC at Marquette Univ., Milwaukee (Sathyan Subbiah), and the 2006 ASME MSEC in Ypsilanti, MI (Sathyan Subbiah).

6. Presentation by the PI to graduate students and faculty in the Department of Mechanical Engineering at the Indian Institute of Technology, Bombay on June 8, 2004 and July 8, 2005.

7. Presentation by the PI to graduate students and faculty in the Department of Mechanical Engineering at the Univ. of Connecticut, Storrs, CT on Nov. 5, 2004.

8. Presentation by the PI at the ICAMDD Conference in Goa, India on Dec. 15, 2005.

9. Presentation by the PI to graduate students and faculty in the Department of Mechanical Engineering at Seoul National University, Seoul, South Korea on July 18, 2006.

10. Presentation by the PI to graduate students and faculty in the Department of Mechanical & Aerospace Engineering at the Univ. of Florida, Gainesville, FL, May 1, 2007.

Journal Publications

Kai Liu and Shreyes N. Melkote, "A Strain Gradient Based Finite Element Model for Micro/Meso-Scale Orthogonal Cutting Process", Proceedings of the 2004 Japan USA Symposium on Flexible Automation, p. 1, vol. CD-ROM, (2004). Published

S. Joshi and S. N. Melkote, "An Explanation for the Size-Effect in Machining Using Strain Gradient Plasticity", Transactions of ASME, Journal of Manufacturing Science & Engineering, p. 679-684, vol. 126, (2004). Published

S. Subbiah and S.N. Melkote, "On the Size-Effect in Micro-Cutting at Low and High Rake Angles", Proceedings of IMECE04, p. 1, vol. CD-ROM, (2004). Published

S. Subbiah and S.N. Melkote, "The Constant Force Component Due to Material Separation and its Contribution to Size-Effect in Specific Cutting Energy", Transactions of ASME, Journal of Manufacturing Science & Engineering, p. 811, vol. 128, (2006). Published

Liu, K. and Melkote, S.N., "Material Strengthening Mechanisms and Their Contribution to Size Effect in Micro-Cutting", ASME Transactions, Journal of Manufacturing Science & Engineering, p. 730, vol. 128, (2006). Published

K. Liu and S.N. Melkote, "Material Strengthening Mechanisms and Their Contribution to Size Effect in Micro-Cutting", Proceedings of the ASME IMECE, p. 1, vol. CD-ROM, (2005). Published

K. Liu and S.N. Melkote, "Effect of Plastic Side Flow on Surface Roughness in Micro-Turning Process", International Journal of Machine Tools and Manufacture, p. 1778, vol. 46, (2006). Published

Ng, C.K., Melkote, S.N., Rahman, M., Kumar, A.S., "Experimental Study of Micro and Nano Scale Cutting of Aluminum 7075-T6", International Journal of Machine Tools and Manufacture, p. 929, vol. 46, (2006). Published

Subbiah, S., Newton, T., Melkote, S.N., "On the Performance of Binderless cBN in Interrupted Hard Turning", Transactions of NAMRI/SME, p. 389, vol. 34, (2006). Published

Subbiah, S. and Melkote, S.N., "Evaluation of Atkins' Model of Ductile Machining Including the Material Separation Component", Journal of Materials Processing Technology, p. 398, vol. 182, (2007). Published

Liu, K. and Melkote, S.N., "Finite Element Analysis of the Influence of Tool Edge Radius on Size Effect in Orthogonal Micro-Cutting Process", International Journal of Mechanical Sciences, p. 650, vol. 49, (2007). Published

Liu, K., Subbiah, S., and Melkote, S.N., "Finite Element Study of Strain Gradient Dependent Material Strengthening of Al5083-H116 in Orthogonal Microscale Cutting", Proceedings of the International Conference on Advanced Design and Development of Materials, Goa, India, p. 1, vol. , (2005). Published

Subbiah, S. and Melkote, S.N., "Evidence of Ductile Tearing Ahead of the Cutting Tool and Modeling the Energy Consumed in Material Separation in Micro-Cutting", ASME Transactions, Journal of Engineering Materials and Technology, p. 321, vol. 129, (2007). Published

Subbiah, S. and Melkote, S.N., "Effect of Finite Edge Radius on Ductile Fracture Ahead of the Cutting Tool Edge in Micro-Cutting of Al2024-T3", Materials Science and Engineering A, p. , vol. , (2007). Accepted

Books or Other One-time Publications

Web/Internet Site

Other Specific Products

Contributions

Contributions within Discipline:

The results obtained in this project made the following significant contributions to the field of micro-cutting process mechanics:

1. Demonstrated through analytical modeling efforts (including comparison with experimental data) that strain gradient effects can contribute to the size-effect in cutting at very small length scales.

2. Developed a detailed numerical model of the micro-cutting process incorporating strain gradient effects that demonstrates size-effect.

3. Contributed to a detailed understanding of the relative contributions of strain gradient strengthening, thermal effects and tool edge radius to the size effect in specific cutting energy in micro-cutting.

4. Presented a new perspective on the size-effect phenomenon based on decomposition of the cutting forces into decreasing, increasing, and constant components.

5. Presented visual and quantitative evidence of the presence of a constant force component associated with material separation during chip formation and its contribution to size-effect.

6. Showed through a numerical model the contribution of material separation due to ductile fracture to the total energy consumed in micro-cutting and to the size effect in specific cutting energy.

7. Generated through systematic experiments, valuable data for micro and nanoscale cutting of common engineering alloys such as Al7075 and P-20 mold steel.

8. Developed a surface roughness model for micro-turning that accurately captures the nonlinear increase in roughness at very low feeds.

9. Partially contributed to the development of a mechanistic micro-cutting force model for orthogonal micro-cutting operations.

Contributions to Other Disciplines:

Several of the results obtained to date in the project are applicable to not only micro-scale cutting but also macro-scale cutting processes. In this regard, it has applicability beyond micro-cutting processes.

Contributions to Human Resource Development:

Through this grant, five (5) graduate students (4 doctoral and 1 Master's) and four(4) undergraduate students have been trained in the field of micro-cutting processes and precision machining in general. Note that of the 4 doctoral students, two (2) were only partially supported by this grant.

Contributions to Resources for Research and Education:

A quick stop device has been fabricated for fundamental studies in machining.

Contributions Beyond Science and Engineering:

Categories for which nothing is reported:

Any Book

Any Web/Internet Site

Any Product

Contributions: To Any Beyond Science and Engineering

Final Project Report for DMI-0300457: Research & Education Activities

Project Goals

The goals of the proposed project are to explain the size-effect phenomenon in micro-cutting, and to develop a fundamental understanding of chip formation and surface integrity in micro-cutting of common engineering metals not investigated to date. These goals will be realized through a combination of analytical/numerical modeling and experimental efforts.

Project Objectives

The specific objectives of the project were as follows:

1. Development of analytical/numerical models based on strain gradient plasticity for the 'size-effect' arising from the primary, secondary and tertiary deformation zones in orthogonal micro-cutting.

2. Verification of the 'size-effect' models through orthogonal micro-cutting experiments.

3. Experimental study of the effects of cutting conditions on chip formation and surface integrity in orthogonal micro-cutting process for common engineering ferrous and non-ferrous alloys.

Summary of Activities for Years 1-4

The following were the major activities in this project since its inception in 2003:

1. Development and experimental validation of numerical (finite element) and analytical models of orthogonal micro-cutting to explain the size-effect commonly observed in the specific cutting energy. Specifically, the modeling effort focused on the following aspects of the problem:

    - A finite element model of orthogonal (plane-strain) micro-cutting that accounts for material strengthening due to strain gradient plasticity effects at the micron scale was developed. The model was developed using the ABAQUS/Standard (ver.6.3) software. In addition to accounting for strain gradient induced material strengthening, the model also considers the effect of material strengthening due to decrease in secondary shear zone temperatures with decrease in the uncut chip thickness and the effect of tool edge radius.

    - Experimental validation of the model under a range of micro-cutting conditions.

    - Detailed analysis of the relative contributions of strain gradient induced material strengthening, thermal "hardening" and tool edge radius effects. This was accomplished through simulations conducted using the finite element model.

    - Development of finite element model of orthogonal micro-cutting to examine the role of material separation leading to chip formation due to ductile fracture in causing the size effect in specific cutting energy. This model was implemented in ABAQUS/Explicit (ver.6.3). Unlike the finite element model incorporating strain gradient plasticity effects, which relies on automatic remeshing to simulate chip formation and ignores material separation due to ductile fracture, this model makes use of an accumulated damage criterion based on a strain, strain-rate and temperature dependent fracture strain.

- Experimental validation of the ductile fracture-based material separation model. Model validation experiments were performed for two ductile materials (OFHC Copper and Al2024-T3) and over a range of cutting speeds and uncut chip thickness values.

- Detailed analysis of energy consumed in material separation and its contribution to the size-effect in specific cutting energy. The stress state ahead of the tool tip was analyzed to determine if the conditions generated in micro-cutting are conducive to ductile fracture. In addition, the effect of tool edge radius on material separation due to ductile fracture was also analyzed.

- Development of a dislocation theory based analytical model to estimate the constant force component responsible for material separation due to ductile fracture in micro-cutting.

2. Modeling the influence of plastic side flow in micro-turning on the resultant surface roughness. This was accomplished by combining a material rheological factor that is a function of the material strength and is derived from an indentation-scratch model with kinematic surface roughness in turning.

3. Novel orthogonal micro-cutting experiments to isolate the constant force component responsible for material separation during chip formation. Both low speed and high speed micro-cutting tests were performed. Some of the high speed tests using a hammer-pin type quick-stop device were carried out by the graduate student at IIT-Bombay in India.

4. Novel orthogonal micro-cutting tests to show experimental evidence of ductile fracture at the chip root. This evidence was obtained by viewing the instantaneous chip root in an SEM.

5. Experiments to understand the influence of tool edge radius on material separation due to ductile fracture.

6. Detailed experimental study of chip formation, cutting forces, and surface finish in microscale (up to 2 microns uncut chip thickness) and nanoscale (down to 10 nm uncut chip thickness) cutting of aluminum 7075-T6 and P20 mold steel. These tests were performed on a Toshiba Ultraprecision Machine Tool located in Department of Mechanical Engineering at the National University of Singapore.

7. Training a total of 4 Ph.D. students (Primary students: Dr. Kai Liu and Dr. Sathyan Subbiah; Partially supported students: Dr. Sangil Han and Mr. Ramesh Singh), 1 M.S. student (Mr. Chee Keong Ng), and 4 NSF REU students (Mr. Thomas Newton, Mr. Issac Penny, Mr. Matthew Alberts, and Mr. Jose Rafael Martinez). The REU students received hands-on training on various aspects of micro-cutting as they worked with the graduate students.

8. A couple of the graduate students, Dr. Sathyan Subbiah and Mr. Ramesh Singh, volunteered their time at inner city high schools to tutor students in mathematics.

9. Dissemination of research results through several technical presentations (at meetings, conferences) and seminars, and refereed and non-refereed publications in major manufacturing research conferences and leading technical journals (9 journal publications, 3 peer-reviewed conference publications, 1 non-refereed publication). See under "Publications" and "Presentations" sections of the report for more details.

Activity Summary for Year 4

The major activities of the project during the period 1/06 through 03/07 are as follows:

1. Experimental and modeling work was carried out to understand the influence of tool edge radius on material separation due to ductile fracture. Some of the PCD tools used in the experiments were donated by Kennametal Inc. This study was successfully completed in September 2006.
2. Mr. Ramesh Singh, a doctoral student working in the area of laser-assisted mechanical micromachining, was hired on this project from December '06 through March '07 to develop a mechanistic model for prediction of cutting and thrust forces in orthogonal micro-cutting. This force model is simpler to apply for practical micro-cutting applications than the numerical models developed earlier. Mr. Mathew Alberts worked with Mr. Singh as an REU student at different times in Fall 2007. Mr. Rafael Martinez worked with Mr. Singh as an REU student in Spring 2007.
3. Micro-cutting experiments were conducted to validate the mechanistic force model.
4. Mr. Sathyan Subbiah successfully completed his Ph.D. degree requirements.

Activity Summary for Year 3

The major activities of the project during the period 1/05 through 12/05 are as follows:

1. A new NSF REU student, Mr. Tommy Newton, was recruited as a replacement for Mr. Issac Penny, who moved on to another project. Mr. Newton is one of our top undergraduates with a very high GPA (major GPA: 4.0) with background in machining. Mr. Newton worked under the supervision of graduate student Sathyan Subbiah and carried out experiments on two different types of cBN tools for interrupted cutting of hardened steels. This small project was meant to introduce Mr. Newton to precision machining research.

2. Mr. Sangil Han, a doctoral candidate in the PI's group, was recruited for from November 2005 – March 2006 to assist with some of the experimental work that Mr. Newton and Mr. Subbiah were engaged in.

3. The effort aimed at developing a detailed numerical (finite element) model of orthogonal micro-cutting including strain gradient effects was completed in November 2005 by graduate student Kai Liu. The model was experimentally verified and used in the development of a surface roughness prediction model for the micro-turning process. In addition, a detailed

analysis of the relative contributions of strain gradient induced material strengthening and material strengthening due to decrease in cutting temperatures with decrease in uncut chip thickness was carried out.

4. Graduate student Chee Keong Ng completed his experimental investigation of micro (up to 2 microns) and nanoscale (as low as 10 nm) orthogonal cutting of common engineering alloys – Al7075-T6 and P-20 mold steel. The chip shape, forces, and other variables of the cutting process such as shear angle, mean coefficient of friction were analyzed. Conventional scale cutting mechanics models such as Merchant's model and Oxley's parallel-sided shear zone model were also evaluated to determine their validity for micro/nanoscale cutting conditions.

5. Work on investigation of the role of ductile tearing/crack formation ahead of the tool tip on energy consumption in microscale cutting (and hence on size effect) was continued. Orthogonal cutting experiments on Al2024 were conducted to determine if the prior evidence of ductile tearing ahead of the tool tip (in OFHC Copper) was also present in this new material. Some of these tests (quick stop type) were conducted by Sathyan Subbiah at the IIT, Bombay due to availability of a quick stop device. A similar device could not be located in machining research labs around the U.S. despite several inquiries.

6. A finite element model of orthogonal micro-cutting that makes use of a Johnson-Cook type ductile fracture criterion based on strain, pressure and temperature was employed to simulate chip formation and forces in orthogonal micro-cutting of Al2024. The predicted forces at different uncut chip thickness values were compared against the measured forces. A detailed analysis of the increase in energy consumption with decrease in uncut chip thickness was performed. In addition, a detailed analysis of the complex stress state ahead of the tool tip and its possible role on ductile tearing was carried out.

7. A total of 8 journal papers were submitted for publication in leading journals in the manufacturing field. Of these 8 papers, 5 of them are currently in press and the remaining 3 are in review. Of the 5 accepted papers, one of them has been co-authored by the NSF REU student, Mr. Tommy Newton, who will be presenting the paper at the 2006 NAMRC at Marquette University in Milwaukee. In addition, 1 peer reviewed conference paper and one non-refereed conference paper were presented by graduate student Kai Liu at the 2005 ASME IMECE and at the 2005 International Conference on Advanced Materials Design and Development (ICAMDD) in Goa, India.

8. Mr. Chee Keong Ng and Dr. Kai Liu successfully completed their M.S. and Ph.D. degrees respectively.

9. Mr. Sathyan Subbiah made a poster presentation of his work at the ICAMDD in Goa, India in December 2005.

10. The PI delivered a departmental seminar titled "Mechanical and Laser-Assisted Micromachining Research: An Overview" in the Department of Mechanical Engineering, Indian Institute of Technology, Bombay on July 8, 2005.

11. Mr. Sathyan Subbiah volunteered his time as a Math tutor in inner city schools (Grady High School – Elementary Math and AP Calculus) in Atlanta.

Activity Summary for Year 2

The major activities of the project during the period 1/04 through 12/04 are as follows:

1. An undergraduate research assistant (Mr. Issac Penny) was finally recruited in September 2004 to work on the NSF REU supplement. He received training in the use of laboratory equipment during the Fall semester of 2004.

2. Refinements were made to the numerical (finite element) model of micro-cutting developed during the previous year. Specifically, the adaptive re-meshing routine was refined to yield better and somewhat faster simulation results. Simulations were carried out to validate the coupled thermo-mechanical portion of the model against results obtained from other commercially available finite element code (DEFORM 2-D). In addition, model was extended to incorporate the effects of temperature in addition to strain and strain gradient effects.

3. Experiments were performed using PCD tools and Al5083 alloy to validate the numerical model under high speed cutting conditions where the contribution of tool-chip interface temperature to size-effect is expected to be dominant (compared to the effect of strain gradient). Cutting forces were measured in these experiments as a function of uncut chip thickness (20 – 200 microns). Experimental results were compared with numerical model simulations.

4. Detailed orthogonal micro-cutting tests on OFHC copper were performed at increasing positive rake angles ranging from 30 deg. to 70 deg. in order to isolate the constant force component associated with material separation in ductile metals. This experiment was aimed at obtaining proof of existence of the constant force component as well visual evidence of cracking due to ductile tearing ahead of the tool tip. Cutting force data, micrographs of the chip section, and SEM images of the region ahead of the tool tip were obtained.

5. An analytical model based on dislocation fracture mechanics for the constant force component responsible for material separation during cutting was developed and compared with the experimental data obtained in the aforementioned activity.

6. One of the graduate students (Mr. Chee Keong Ng) spent the summer at the National University of Singapore conducting a detailed experimental investigation of microscale (up to 2 microns) and nanoscale (as low as 10 nm) cutting of non-ferrous (Al7075-T6) and ferrous (P-20 mold steel) on a Toshiba ultra-precision CNC machine. Cutting force data, chip morphology data, tool wear data, and machined surface morphology data were collected. Additional micro-cutting tests (from 10 to 200 microns) on the ferrous material (P-20) were performed on the Hardinge T42 Superprecision Lathe in the Precision Machining Lab at Georgia Tech. Similar data were collected.

7. The micro-/nano-scale cutting data collected at NUS and GT were analyzed using the Classic Merchant's model that ignores edge radius effects as well as a more recent model developed by Manjunathaiah and Endres that accounts for edge radius effects.

8. Two papers based on the work carried out in this project were presented at major conferences in 2004. The first paper dealt with the numerical strain gradient plasticity model and was

presented at the 2004 Japan-USA Conference on Flexible Automation held in Denver, Colorado from July 19-21, 2004. Another paper based on the work on size-effect due to the constant force component was presented at the 2004 ASME IMECE held in Anaheim, CA from Nov. 14-19, 2004. In addition, an extended version of the latter paper was submitted in Nov. 2004 for possible publication in the ASME Transactions, Journal of Manufacturing Science & Engineering. Finally, an abstract for a new paper on the numerical model of micro-cutting incorporating strain gradient plasticity has been submitted to the 2005 JSME/ASME Conference on Materials and Processing to be held in Seattle, WA.

9. The PI and two of his PhD students (Kai Liu and Sathyan Subbiah) presented a poster on this project at the 2004 NSF Research Conference held in Dallas, Texas. A paper was also written for this conference.

10. The PI delivered a seminar titled "Some Investigations of Size-Effect in Micro-Cutting Process" in the Department of Mechanical Engineering, University of Connecticut on Nov. 5, 2004.

Activity Summary for Year 1

The major activities of the project since its start in April 2003 are as follows:

1. Two fresh (1 M.S. and 1 Ph.D.) and one existing (Ph.D.) graduate students were enlisted for the project. The existing student is currently working part time on this project and part time on another NSF grant (DMI-0100176). The hiring of the undergraduate student (for the REU supplement) has been put off till the Spring semester when the development of the orthogonal micro-cutting setup and experiments is expected to start.

2. Additional literature search in the area of size effect, diamond turning, and micro-machining to determine the status quo in the understanding of size-effect.

3. A strain gradient based numerical (finite element) model has been developed to explain the size effect in micro-cutting. Strain gradient is incorporated into the constitutive material model to reflect the effects of highly localized inhomogeneous deformation and steep strain gradients in micro-cutting processes. An adaptive re-meshing technique is used to simulate a more physically based chip formation and obtain better resolution of the strain gradient. Note that initial efforts have focused on numerical modeling of the strain gradient plasticity effect. Later work will focus on analytical modeling of the orthogonal cutting process including strain gradient effects.
4. Simulation results from the new model are compared with those from a finite element model based on conventional plasticity to examine the effects of strain gradient on the distributions of plastic strain, stress, temperature and specific cutting energy.

5. Conducted preliminary orthogonal machining experiments on OFHC copper tubes at high rake angles to study and model the constant force component. Initial experiments have been performed with a non-ferrous material. However, future experiments will involve a ferrous material as well.

6. Visits to the National University of Singapore by the PI (November 2003) and graduate student, Mr. Chee Keong Ng (December 2003) to identify specific needs for carrying out orthogonal cutting tests at very low uncut chip thickness values on ferrous and non-ferrous materials. These tests are tentatively scheduled to be carried out in Summer 2004.

7. One of the graduate students (Sathyan Subbiah) is involved in providing math tutoring to elementary school students in the Atlanta area through Georgia Tech's Center for Education Integrating Science, Mathematics and Computing (CEISMC) via their Mentoring Program.

8. Invited presentation on "Some Ideas on Size-Effect in Micro-Cutting" by PI in the Lab-Fresh Session on Machining Processes Research organized by the Manufacturing Engineering Division of ASME at the IMECE in Washington, DC from Nov. 15-21, 2003.

9. Paper titled "A Strain Gradient Based Model for Micro/Meso-Scale Orthogonal Cutting Process" co-authored by Kai Liu and Shreyes N. Melkote submitted to the 2004 Japan/USA Symposium on Flexible Automation to be held in Denver, CO in July 2004.

Publications

1. Liu, K. and Melkote, S.N., "A Strain Gradient Based Finite Element Model for Micro/Meso-Scale Orthogonal Cutting Process," <u>Proceedings of the 2004 Japan-USA Symposium on Flexible Automation</u>, Denver, CO, July 2004, Paper No. UL_048, p. 1-8.

2. Liu, K., and Melkote, S.N., "Material Strengthening Mechanisms and Their Contribution to Size Effect in Micro-Cutting," <u>ASME Transactions, Journal of Manufacturing Science & Engineering</u>, Vol. 128, No. 3, pp. 730-738, 2006; also in <u>Proceedings of 2005 ASME International Mechanical Engineering Congress & Exposition</u>, Orlando, FL, MED Vol. 16-2, pp. 1147-1156, 2005.

3. Liu, K. and Melkote, S.N., "Effect of Plastic Side Flow on Surface Roughness in Micro-Turning Process," <u>International Journal of Machine Tools and Manufacture</u>, Vol. 46, No. 14, 2006, pp. 1778-1785.

4. Ng, C.K., Melkote, S.N., Rahman, M., Kumar, A.S., "Experimental Study of Micro and Nano Scale Cutting of Aluminum 7075-T6," <u>International Journal of Machine Tools and Manufacture</u>, Vol. 46, No. 9, 2006, pp. 929-936.

5. Subbiah, S. and Melkote, S.N., "The Constant Force Component due to Material Separation and its Contribution to Size-Effect in Specific Cutting Energy," <u>ASME Transactions, Journal of Manufacturing Science & Engineering</u>, Vol. 128, No. 3, 2006, pp. 811-815.

6. Subbiah, S., Newton, T., Melkote, S.N., "On the Performance of Binderless cBN in Interrupted Hard Turning," <u>Transactions of NAMRI/SME</u>, Vol. 34, 2006, pp. 389-396.

7. Subbiah, S. and Melkote, S.N., "Evaluation of Atkins' Model of Ductile Machining Including the Material Separation Component," <u>Journal of Materials Processing Technology</u>, Vol. 182, No. 1-3, 2007, pp. 398-404.

8. Liu, K. and Melkote, S.N., "Finite Element Analysis of the Influence of Tool Edge Radius on Size Effect in Orthogonal Micro-Cutting Process," International Journal of Mechanical Sciences, Vol. 49, No. 5, 2007, pp. 650-660.

9. Liu, K., Subbiah, S., and Melkote, S.N., "Finite Element Study of Strain Gradient Dependent Material Strengthening of Al5083-H116 in Orthogonal Microscale Cutting," Proceedings of the International Conference on Advanced Design and Development of Materials, Goa, India, December 14-16, 2005, p. 1-9.

10. Subbiah, S. and Melkote, S.N., "Evidence of Ductile Tearing Ahead of the Cutting Tool and Modeling the Energy Consumed in Material Separation in Micro-Cutting," ASME Transactions, Journal of Engineering Materials and Technology, Vol. 129, No. 2, 2007, pp. 321-331; also in Proceedings of the ASME International Conference on Manufacturing Science and Engineering (MSEC), 2006, p. 1-10.

11. Subbiah, S. and Melkote, S.N., "Effect of Finite Edge Radius on Ductile Fracture Ahead of the Cutting Tool Edge in Micro-Cutting of Al2024-T3," accepted, Materials Science & Engineering, ***in press***.

Presentations

1. Subbiah, S., Liu, K., Melkote, S.N., Joshi, S.S., "Some Investigations of Size-Effect in Micro-Cutting," invited presentation at the Lab-Fresh Session on Machining Processes, ASME IMECE, Washington, D.C., Nov. 20, 2003.

2. "Some Investigations of Size-Effect in Micro-Cutting Process", Department of Mechanical Engineering, Indian Institute of Technology, Bombay, India, June 8, 2004.

3. "Some Investigations of Size-Effect in Micro-Cutting Process", Department of Mechanical Engineering, University of Connecticut, Storrs, CT, Nov. 5, 2004.

4. "Mechanical and Laser-Assisted Micromachining Research: An Overview," Department of Mechanical Engineering, Indian Institute of Technology, Bombay, India, July 8, 2005.

5. "Finite Element Study of Strain Gradient Dependent Material Strengthening of Al5083-H116 in Orthogonal Microscale Cutting," International Conference on Advanced Materials Design & Development, Goa, India, 15 December 2005.

6. Subbiah, S. and Melkote, S.N., "Finite Element Study of Energy Consumed in Material Separation in Micro Cutting Process," poster presentation at the International Conference on Advanced Materials Design & Development, Goa, India, 14-16 December 2005. **(Winner of Best Poster Presentation Award for S. Subbiah).**

7. "Mechanical and Laser-Assisted Micromachining Research" Department of Mechanical Engineering, Seoul National University, Seoul, Korea, July 18, 2006.

8. "Analysis of the Size-Effect in Micro-Cutting Processes" Department of Mechanical & Aerospace Engineering, University of Florida, Gainesville, May 1, 2007.

Final Project Report for DMI-0300457: Summary of Key Findings

Summary of Significant Project Findings

The major research findings of this project in the following specific areas are summarized below: 1) Analysis of size-effect due to strain gradient, thermal and tool edge radius effects, 2) Analysis of size-effect due to material separation via ductile fracture, 3) Effect of plastic side flow on surface roughness in micro-turning, 4) Experimental investigation of micro-/nano- scale cutting of ferrous and non-ferrous engineering alloys, and 5) NSF REU project findings.

1. Analysis of size effect due to strain gradient, thermal and tool edge radius effects

- The finite element model of orthogonal micro-cutting incorporating the effects of strain gradient plasticity and thermal softening/hardening was found to be capable of predicting the size effect in specific cutting energy over a range of uncut chip thicknesses (2-200 microns) and cutting speeds (1.2 – 240 m/min). The model predictions of the forces and specific cutting energy are in good agreement with measured values.
- Strain gradient strengthening contributes significantly to the size-effect at low cutting speed (< 10 m/min) and small uncut chip thickness (< 10 μm)
- Temperature dependence of flow stress is the dominant cause of size effect at high cutting speeds (> 200 m/min) and larger uncut chip thickness (> 20 μm). The size effect is caused by material strengthening due to drop in the secondary shear zone temperature.
- Strain gradient strengthening is more dominant than the temperature effect at high cutting speed (> 200 m/min) and small uncut chip thickness (< 10 μm).
- Tool edge radius accounts for only part of the size effect in micro cutting.
- The contribution of edge radius to size effect arises from: (a) increase in size of plastic shear zone around the tool tip, and (b) higher frictional energy dissipation due to increased tool-chip contact length.
- Under cutting conditions where the strain gradient effect is dominant the nonlinear increase in specific cutting energy occurs near the intrinsic material length scale *l*.

2. Analysis of size-effect due to material separation via ductile fracture

- By viewing specific cutting energy as a ratio of two numbers the cause for the size effect is attributed to an increasing component of the cutting force and/or a constant force component.
- Special experiments at high rake angles can serve to isolate the constant force component. Cutting force trends at high rake angles (up to 70^{o}) that minimize the shear in the chip indicate that the force tends to a constant value at higher rake angles approaching 90^{o}.

- SEM images of the chip-workpiece interface for OFHC copper and Al2024-T3 show clear evidence of ductile fracture ahead of the tool leading to chip formation.
- Ductile fracture occurs in a narrow zone spanning the width of cut and directly in front of the cutting tool edge. These observations put to rest criticisms about the use of a pre-defined sacrificial layer in numerical simulations to model chip separation either by node release or element deletion. As long as physically-based fracture models or damage models pertaining to the nature of failure are used to release the nodes or delete elements, it is argued here that this approach is valid.
- The crack extension force associated with ductile fracture is found to be comparable with the constant cutting force observed at high rake angles. With shear in the chip being minimal at such high rake angles, the mechanism of chip formation (material separation) is primarily ductile fracture or ductile tearing ahead of the tool.
- The numerical model incorporating sacrificial layers and damage simulated by a J-C damage model was found to be in good agreement with the measured cutting and thrust forces (max. error < 9% and 15%, respectively) for micro-cutting of Al2024-T3.
- The stress state ahead of the cutting tool shows that the pressure is positive closer to the cutting edge and negative further ahead. An element in the sacrificial layer changes its stress state to tensile as it approaches the cutting tool leading to ductile fracture.
- Analysis of energy consumed in micro-cutting indicates that the percentage of energy consumed in plastic dissipation in the chip decreases with uncut chip thickness, while that of the sacrificial layer increases.
- In absolute energy terms, the energy consumed in material separation is seen to not vary significantly as the uncut chip thickness is reduced. This appears to support the hypothesis that there is always a constant force component associated with cutting.
- The size-effect in specific cutting energy is clearly observed in Al2024-T3. The specific energy associated with material separation is found to increase substantially with decrease in uncut chip thickness and plays an important role in explaining the scaling in the specific cutting energy.
- The chip-workpiece junction consists of an interface zone of metal when cutting with an edge-radius tool. Such an interface is absent in the case of an up-sharp tool (with edge radius much smaller than the uncut chip thickness).
- The interface zone of metal is found to fracture at three locations: one, at the upper edge closer to the chip, two, in the middle of the zone, and three, at the lower edge closer to the workpiece surface.
- Based on observation, it is hypothesized that an element of metal approaching the edge-radius tool tip wraps around the edge and then is stretched in opposing directions: in the direction of the chip-flow and in the direction of workpiece surface movement. Depending on which area is weaker and how strong these stretching effects are the element of metal can fracture at the upper, middle and/or the lower edges of the interface zone.

- The mean stresses in front of the tool are tensile even with an edge radius tool indicating favorable conditions for fracture to occur.
- All stress components in front of the tool tip are consistently lower with the edge radius tool than the sharp tool indicating that a sharp tool provides a more favorable condition for fracture to occur.
- A higher percentage of energy is spent in the sacrificial layer and the sub-surface in the case of the edge radius tool than the sharp tool.

3. Effect of plastic side flow on surface roughness in micro-turning
   - It is found that most of the discrepancy between the theoretical and measured surface roughness in micro-turning of Al5083-H116 alloy is largely due to the additional surface roughening caused by plastic side flow.
   - The increase in roughness with decrease in feed after reaching a minimum can be attributed to increased plastic side flow caused by the strain-gradient induced strengthening of the material directly ahead of the tool.
   - Significant improvement in roughness prediction is achieved using the developed surface roughness model. The percentage error of the prediction using the developed model is less than 15% for all feeds investigated.

4. Experimental investigation of micro-/nano- scale cutting of ferrous (P-20) and non-ferrous (Al7075-T6) engineering alloys. The key findings for Al7075-T6 are (Ng, et al., 2006):
   - Continuous chips are observed over the entire range of undeformed chip thicknesses (10 – 2000 nm) investigated.
   - The cutting force exhibits an approximately linear relationship with the undeformed chip thickness when cutting at undeformed chip thicknesses greater than the edge radius of the tool (60 ~ 100 nm).
   - When the undeformed chip thickness is smaller (10 – 60 nm) than the edge radius of the tool, a non-linear variation in the cutting forces is observed.
   - A size effect in the specific cutting energy is observed at undeformed chip thicknesses smaller (10 – 60 nm) than the edge radius of the tool.
   - The cutting speed has a negligible effect on the cutting force at undeformed chip thicknesses less than ~700nm.
   - The shear angle increases initially and then decreases as the undeformed chip thickness is increased.
   - The mean friction coefficient exhibits a size-effect that can be explained via material strengthening due to decrease in tool-chip interface temperature with decrease in undeformed chip thickness.
   - The machined surface at an undeformed chip thickness smaller than the edge radius of the tool (10 – 60 nm) is rougher than at larger undeformed chip thickness for both cutting speeds (10 m/min and 150 m/min).

5. NSF REU Project Findings:
   - Binderless cBN tools do not perform as well (in terms of tool wear) as high content cBN tools in interrupted micro-cutting of hardened steel at conventional cutting speeds (120 m/min). They tend to wear less than high content cBN tools

at higher cutting speeds (180 m/min).

- The effect of interruption length (used as a parameter to characterize the interruption geometry) on tool wear is more significant than the effect of interruption ratio.
- Surface integrity (white layer formation) is better with a binderless cBN tool than with the high content cBN tool in interrupted micro-cutting of hardened steel.
- The mechanistic orthogonal micro-cutting force model was found to be in good agreement with experimental results.

Summary of Project Findings in Year 4

The following is a summary of the key findings of research activities carried out in Year 4 of the project:

- The study involving the effect of tool edge radius on material separation via ductile fracture showed that the chip-workpiece junction consists of an interface zone of metal when cutting with an edge-radius tool. Such an interface is absent in the case of an up-sharp tool (with edge radius much smaller than the uncut chip thickness).
- The interface zone of metal is found to fracture at three locations: one, at the upper edge closer to the chip, two, in the middle of the zone, and three, at the lower edge closer to the workpiece surface.
- Based on observation, it is hypothesized that an element of metal approaching the edge-radius tool tip wraps around the edge and then is stretched in opposing directions: in the direction of the chip-flow and in the direction of workpiece surface movement. Depending on which area is weaker and how strong these stretching effects are the element of metal can fracture at the upper, middle and/or the lower edges of the interface zone.
- The mean stresses in front of the tool are tensile even with an edge radius tool indicating favorable conditions for fracture to occur.
- All stress components in front of the tool tip are consistently lower with the edge radius tool than the sharp tool indicating that a sharp tool provides a more favorable condition for fracture to occur.
- A higher percentage of energy is spent in the sacrificial layer and the sub-surface in the case of the edge radius tool than the sharp tool.
- The mechanistic micro-cutting force model was developed and experimentally validated under a range of uncut chip thickness values and cutting speeds for H-13 steel. The model was found to be in good agreement with the measured forces.

Summary of Findings in Year 3

The major findings of the work performed from 1/05 through 3/06 are summarized below.

1. Numerical Model Incorporating Strain Gradient Plasticity
   - Detailed analysis of the effects of material strengthening due to strain gradient

effect and due to decrease in thermal softening on the size effect in specific cutting energy shows that strain gradient is responsible for much of the nonlinearity in the specific cutting energy at small uncut chip thickness values at low and high cutting speeds. Although the contribution of temperature effects is higher at higher cutting speeds, it is more significant than the strain gradient effect only at larger uncut chip thickness values [1, 2-4].

- Detailed analysis of force data available in the literature for the effect of cutting edge radius (or edge hone) on size effect reveals that the nonlinearity in specific cutting energy does not always start at or near an uncut chip thickness equal to the edge radius. In fact, a stronger correlation is observed between the start of the nonlinear increase in specific cutting energy and the intrinsic material length scale introduced by strain gradient plasticity [1, 5].
- A new model for prediction of surface roughness in micro turning was developed [6]. This model explicitly accounts for the effect of material deformation due to side flow via an indenter scratch model. The model accounts for material strengthening due to strain gradient plasticity via the finite element model described in [1, 2-4]. The model was experimentally verified and found to yield good results [1, 6].
- A most interesting finding from the surface roughness model for micro-turning is that it clearly explains the source of deviation between the theoretical surface roughness (based on kinematics and tool geometry only) and the measured surface roughness at very small feeds [6]. Specifically, it shows that measured roughness is higher than the theoretical surface roughness unless one accounts for size effect. This fact was speculated by Shaw [7] but not demonstrated via a model. The current work confirms Shaw's hypothesis through a detailed model.

2. Size-Effect Due to Constant Force Required for Material Separation
    - In addition to the very slow speed orthogonal micro-cutting tests on OFHC copper reported earlier, quick stop tests on both OFHC copper and on Al2024-T3 were performed at higher cutting speeds (up to 150 m/min) and at 110 μm uncut chip thickness. Analysis of results from these tests shows clear evidence of ductile tearing and fracture just ahead of the tool tip in both materials – an observation consistent with earlier findings for OFHC copper at very slow cutting speeds. The region of ductile tearing was found to be restricted to a very narrow zone just ahead of the tool tip [8]. This evidence supports the assumption that the ductile crack/fracture path is roughly straight ahead of the tool edge.
    - A finite element model developed in ABAQUS Explicit to simulate the effect of material separation due to ductile fracture was experimentally verified for Al2024-T3 over a range of uncut chip thickness values (50 – 110 microns). The model incorporates ductile fracture of the work material via a Johnson-Cook damage model found in the literature. The effects of pressure, strain rate and temperature on the strain-to-fracture are accounted for. Additionally, damage accumulation was taken into consideration in evaluating the fracture criterion. The simulated forces were found to compare well with the measured forces (max. error of 9%) [8].
    - Analysis of the hydrostatic stress distribution immediately ahead of the tool tip

using the finite element model shows that the stress state is tensile indicating that conditions for ductile fracture are favorable [8].

- Analysis of the energy consumed in material separation relative to energy consumed in shear and friction reveals that energy consumed in material separation increases significantly with decrease in uncut chip thickness whereas the other energies remain fairly unchanged. This supports the hypothesis that energy consumed in material separation can contribute to size effect in micro-cutting. This effect is found to be more pronounced at higher positive rake angles [8].
- Mr. Sathyan Subbiah received a best poster presentation award at the ICAMDD in Goa, India, in December 2005.

3. NSF REU Findings
   - Binderless cBN tools do not perform as well (in terms of tool wear) as high content cBN tools in interrupted micro-cutting of hardened steel at conventional cutting speeds (120 m/min). They tend to wear less than high content cBN tools at higher cutting speeds (180 m/min) [9].
   - The effect of interruption length (used as a parameter to characterize the interruption geometry) on tool wear is more significant than the effect of interruption ratio [9].
   - Surface integrity (white layer formation) is better with a binderless cBN tool than with the high content cBN tool in interrupted micro-cutting of hardened steel [9].

References

1. Liu, K. Process Modeling of Micro-Cutting Including Strain Gradient Effects, Ph.D. thesis, Mechanical Engineering, Georgia Tech, October 2005.
2. Liu, K. and Melkote, S.N., "A Strain Gradient Based Finite Element Model for Micro/Meso-Scale Orthogonal Cutting Process," <u>CD-ROM Proceedings of the 2004 Japan-USA Symposium on Flexible Automation</u>, Denver, CO, July 2004, Paper No. UL_048, p. 1-8.
3. Liu, K., and Melkote, S.N., "Material Strengthening Mechanisms and Their Contribution to Size Effect in Micro-Cutting," <u>ASME Transactions, Journal of Manufacturing Science & Engineering</u>, ***in press***; also in <u>Proceedings of 2005 ASME International Mechanical Engineering Congress & Exposition</u>, Orlando, FL.
4. Liu, K., Subbiah, S., and Melkote, S.N., "Finite Element Study of Strain Gradient Dependent Material Strengthening of Al5083-H116 in Orthogonal Microscale Cutting," <u>Proceedings of the International Conference on Advanced Design and Development of Materials</u>, Goa, India, December 14-16, 2005, p. 1-9.
5. Liu, K. and Melkote, S.N., "Effect of Plastic Side Flow on Surface Roughness in Micro-Turning Process," <u>International Journal of Machine Tools and Manufacture</u>, ***in press***.
6. Liu, K. and Melkote, S.N., "Finite Element Analysis of the Influence of Tool Edge Radius on Size Effect in Orthogonal Micro-Cutting Process," submitted, <u>International Journal of Mechanical Sciences</u>, November 2005.

7. Shaw, M.C., *Metal Cutting Principles*, Oxford Univ. Press, 1984, pg. 516.
8. Subbiah, S. and Melkote, S.N., "Evidence of Ductile Tearing Ahead of the Cutting Tool and Modeling the Energy Consumed in Material Separation in Micro-Cutting," submitted, ASME Transactions, Journal of Engineering Materials and Technology, January 2006; also submitted to 2006 ASME Manufacturing Science and Engineering Conference (MSEC).
9. Subbiah, S., Newton, T., Melkote, S.N., "On the Performance of Binderless cBN in Interrupted Hard Turning," Transactions of NAMRI/SME, ***in press***.

Summary of Findings in Year 2

The major findings of the work performed from 1/04 through 12/04 are summarized below.

4. Numerical Model Incorporating Strain Gradient Plasticity

- Experimental validation of the coupled thermo-mechanical finite element model of orthogonal cutting using Al5083 alloy and PCD tool yielded cutting and thrust force predictions within 20% of the measured values (see Fig. 1 below) at a cutting speed of 200 m/min and over an uncut chip thickness range of 20 – 200 microns.

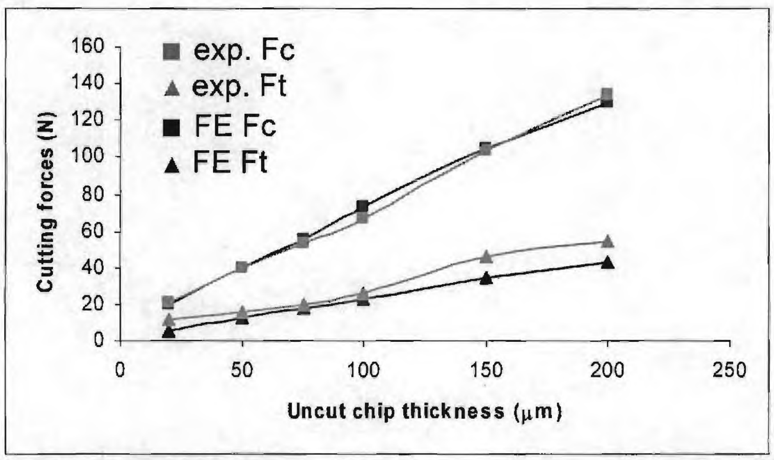


Fig. 1. Predicted vs. measured cutting and thrust forces. Workpiece: Al5083, Tool: PCD (7-10 μm edge radius), Cutting Speed: 200 m/min, Dry Cutting.

- The model shows that the size-effect due to material strengthening arising from reduction in the maximum temperature at the tool-chip interface (secondary shear zone (SSZ)) is significant (see Fig. 2 below) at a cutting speed of 200 m/min over an uncut chip thickness range of 20 – 200 microns.

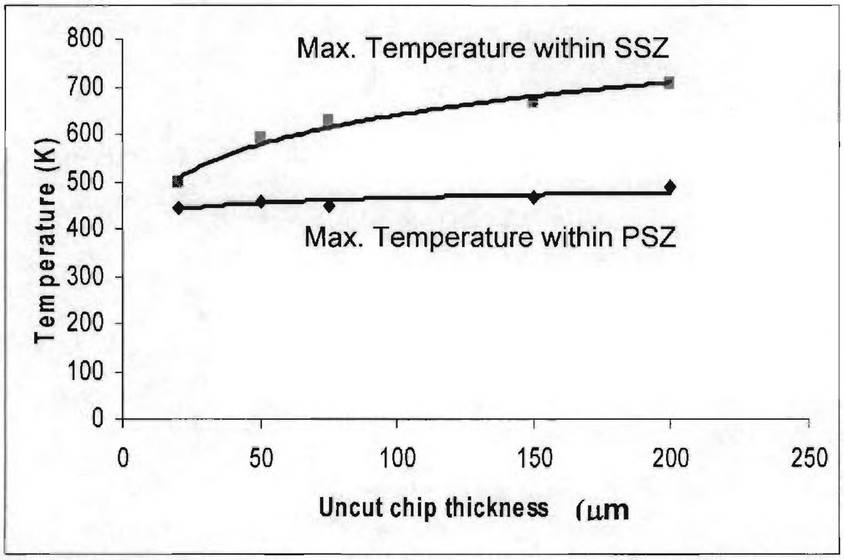


Fig. 2. Simulated max. temperatures. Workpiece: Al5083, Tool: PCD (7-10 µm edge radius), Cutting Speed: 200 m/min.

- At high cutting speeds (200 m/min) where temperature effects are significant, material strengthening due to temperature decrease at in the secondary shear zone accounts for most of the size-effect seen in the specific cutting energy (see Fig. 3 below). The contribution of strain gradient is negligible.

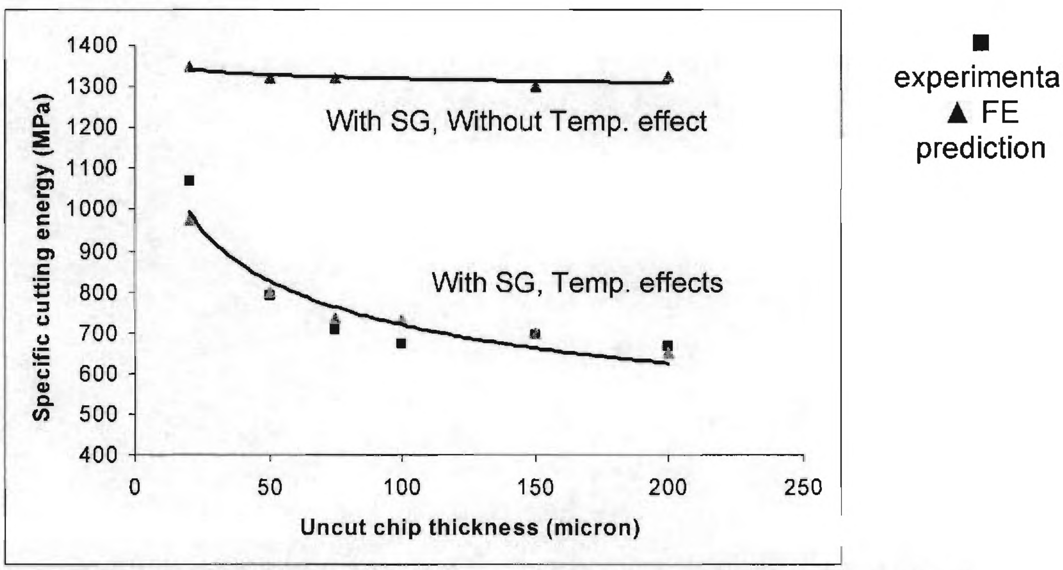


Fig. 3. Specific cutting energy comparison. Workpiece: Al5083, Tool: PCD (7-10 µm edge radius), Cutting Speed: 200 m/min.

5. Size-Effect Due to Constant Force Required for Material Separation

- Detailed orthogonal micro-cutting tests on OFHC copper were performed at increasing positive rake angles ranging from 30 deg. to 70 deg. have shown the presence of a trend towards a constant force component associated with material separation in ductile metals (Fig. 4). The slope of the cutting force is seen to decrease and extrapolation shows that the slope goes to zero in the vicinity of 90° rake angle. Since at hgh rake angles shear is minimum, the force is seen as necessary for material separation.

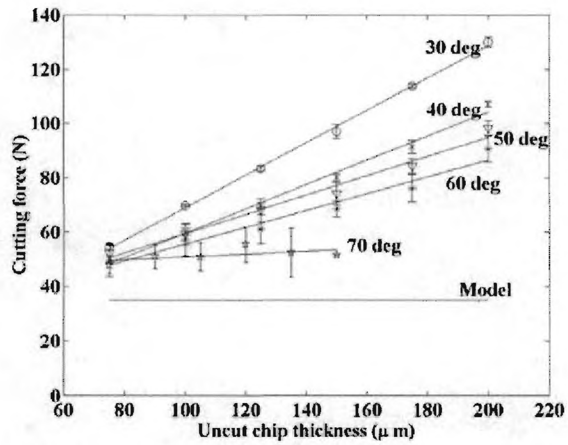


Fig. 4: Cutting force trends at increasing rake angles

- Obtained visual evidence of cracking due to ductile tearing ahead of the tool tip through SEM images (Fig. 5). Strands of copper are seen attached from the underside of the chip to the machined surface. Comparison of this with literature in ductile fracture mechanics confirms this as ductile tearing.

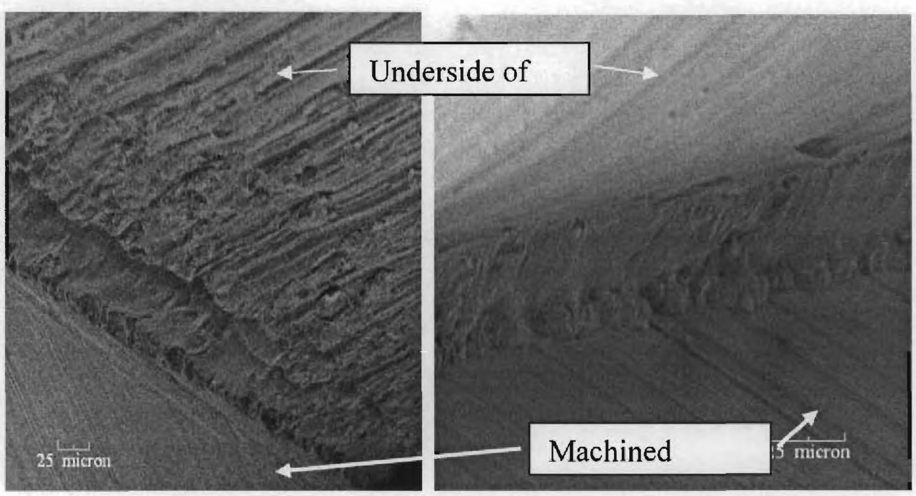


Fig. 5: Evidence of ductile tearing ahead of tool tip (left: 30 deg rake; right: 70 deg rake angle)

- The force required for crack extension in ductile fracture, calculated using a dislocation based approach (Subbiah and Melkote, 2004), was found to be within orders of magnitude of the observed trend towards a constant cutting force component (see Fig. 4).

3. Micro/Nanoscale Cutting Experiments

- Specific cutting energy variation over a large range of uncut chip thickness for cutting of Al7075-T6 shows the trend seen in Fig. 6. It is seen that the non-linearity in the trend begins around 50 nm, which is close to the estimated edge radius of 65 nm for the Single Crystal Diamond insert used in the tests. Similar trends were observed for P-20 mold steel.

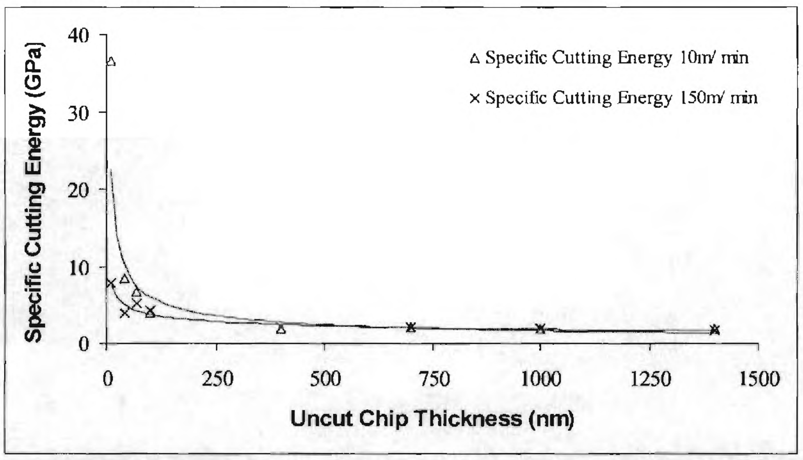


Fig. 6. Specific cutting energy variation with uncut chip thickness for Al7075 workpiece and SCD tool.

- Chip and machined surface morphology changes with uncut chip thickness and cutting speed are seen in Fig. 7 and 8, respectively. Continuous chip formation is observed in Al-7075 down to about 10 nm uncut chip thickness at both low and high cutting speeds. The surface morphology tends to improve with increasing cutting speed. Similar results were found for P-20 mold steel.

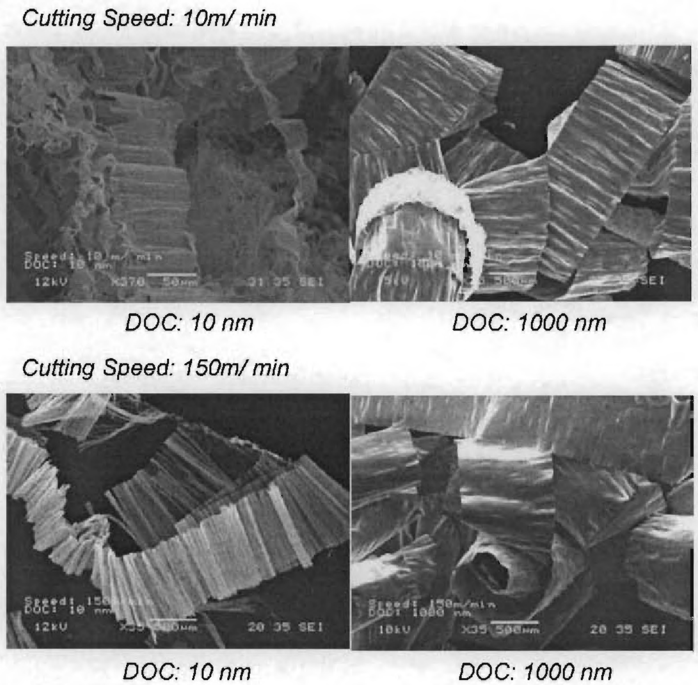


Fig. 7. Chip morphology in nanoscale cutting of Al7075 as a function of depth of cut (uncut chip thickness) and cutting speed.

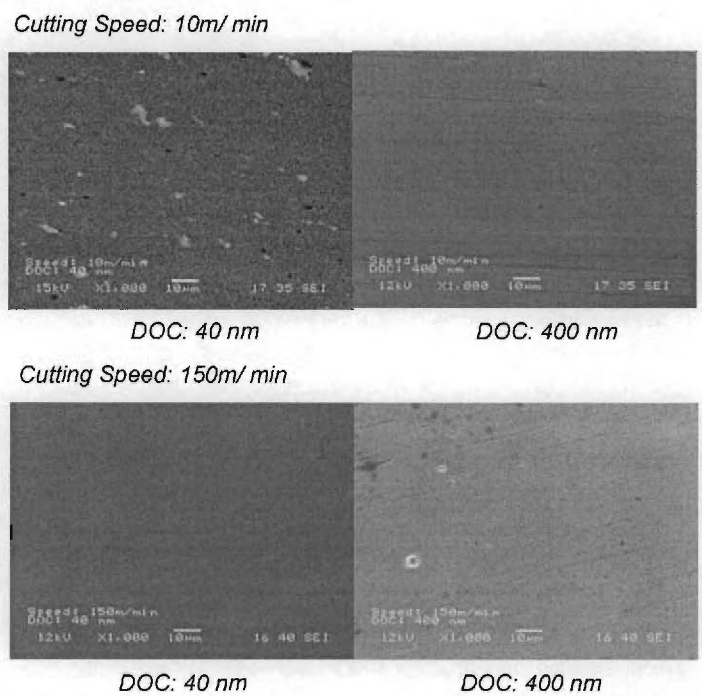


Fig. 8. Surface morphology in nanoscale cutting of Al7075 as a function of depth of cut (uncut chip thickness) and cutting speed.

Summary of Findings in Year 1

To date the major findings of the project in the areas of incorporating a length scale into the material strength model and build analytical and numerical models incorporating strain-gradient plasticity, experimental approach, emphasizing observing, understanding and modeling cutting forces instead of specific cutting energy, and performing experiments to break down and isolate the forces into specific components, are summarized below.

6. Summary of Literature Search

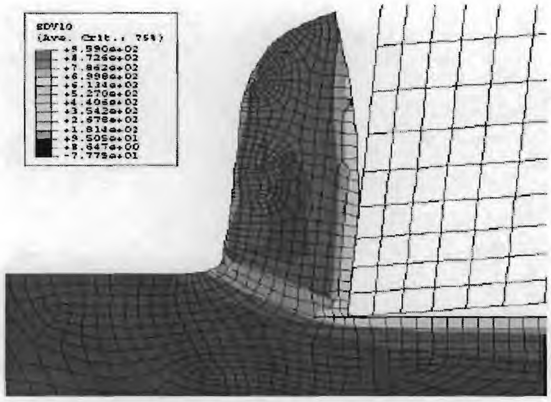
A thorough literature search has been performed in the areas of size-effect, diamond turning, and micro-machining. Several theories in literature were found that seem to explain size-effect, such as those based on inhomogeneities, strain-rate effects, nose-radius effects, strain-gradient effect, sub-surface plasticity, and fracture. Each theory has been substantiated with experimental trends that match the model. It is not clear which theory is correct and whether all of them are correct with some being more applicable in certain regimes. This has also necessitated a fresh look at micro-machining and trying to understand the size-effect phenomenon.

7. Numerical Model Incorporating Strain Gradient Plasticity

- A strain gradient based finite element model (Figure 1) for orthogonal cutting has been developed and used to predict the size effect in micro-cutting (Figure 2). Excluding other influential factors, the developed model is shown to be capable of capturing size effect in the specific cutting energy.

Ignoring thermal softening and strain-rate hardening effects and employing a flow stress model with power-law strain hardening behavior, the following trends were found:

- Strain gradient strengthening is found to have little effect on the distribution of temperature, effective plastic strain and effective stress within the workpiece.
- Strain gradient strengthening leads to higher effective stress in the deformation zones and the finished surface, and lower plastic strain in the primary deformation and secondary deformation zones.
- The strain gradient effect leads to higher cutting temperatures



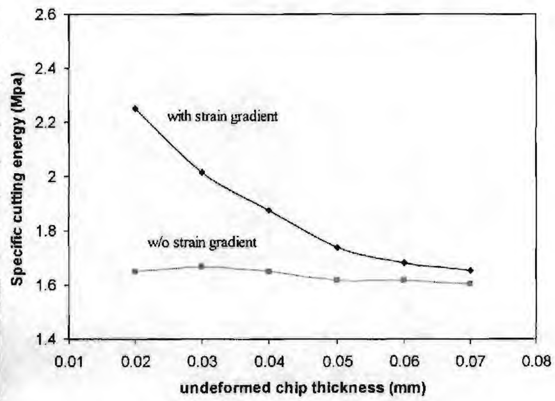


Figure 1: Effective strain gradient contour

Figure 2: Specific cutting energy with and without strain gradient effect

8. Experimental Approach

In orthogonal cutting, for a constant width of cut, the specific cutting force is proportional to the ratio of the cutting force F_c to the undeformed chip thickness (or depth of cut) t_o. This ratio will increase with decreasing undeformed chip thickness under the following conditions: (i) the numerator increases as the denominator decreases, (ii) the numerator remains constant, (iii) the numerator decreases at a lower rate than the denominator. Thus, the cutting force can be conceived as consisting of three components:

$$F_c = F_{const} + F_{inc} + F_{dec},$$

where, F_{const} is that part of the cutting force that does not change with t_o, and F_{inc} increases while F_{dec} decreases with t_o. F_{const} is that part of the cutting force that will always be needed to remove material irrespective of how much material is removed, and should be related to parameters such as the atomic bond energy. F_{inc} could be due to material strength related factors such as an increase in material strength with decrease in the intrinsic length scale, which in turn could be due to factors such as high strain rates, dependence of strength on the strain gradient, or due to inhomogeneities in the material, or some combination of all of these. F_{dec} is the normal decrease in cutting force one would expect to see since the area of cut decreases with t_o. The problem lies in isolating these force components and developing analytical methods to predict them.

The next step is to study the existence of these components and to understand them through experiments. The focus of the ongoing effort is to conduct carefully designed experiments characterized by low undeformed chip thickness to isolate/highlight one of the three force components. The following three types of experiments will be investigated:

- Cutting with high rake angle cutting tools
- Cutting of annealed and highly cold-worked materials
- Cutting nano-crystalline materials

The experimental investigation has begun with high rake angle cutting tools (rake angles in excess of 45 degrees) with OFHC Copper as the workpiece material. Orthogonal cutting tests at 23.9 m/min cutting speed, depths of cut ranging from 10 to 100 μm, and rake angles ranging from 20 to 50 degrees, have been conducted. Preliminary results of these experiments are as follows.

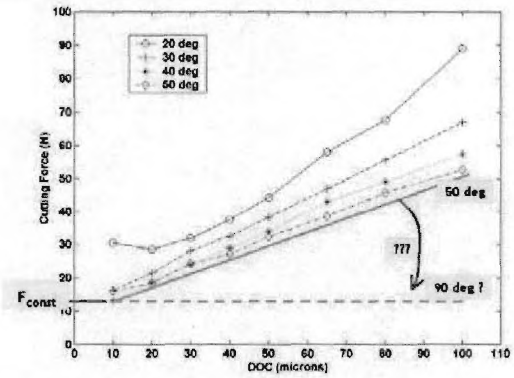


Figure 3: Thrust force at various rake angles

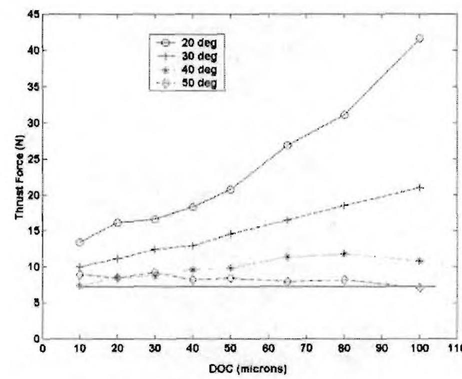


Figure 4: Cutting force at various rake angles

Figure 3 and 4 show the trends in cutting and thrust force, respectively, with depth of cut at various rake angles. It is clear from Fig. 3 that as the rake angle increases the slope in the cutting force seems to be decreasing. Therefore, at a rake of angle of 90 degree the cutting force may tend to become constant. Fig. 4 shows that the thrust force has already become constant at a rake angle of 50 degree. Further efforts are underway to perform experiments at even higher rake angles. Analytical modeling of the observed force trends will also be carried out.

4. NUS Visit

Visits to NUS by the PI and student (Mr. Chee Keong Ng) have yielded information on the specific equipment available at NUS to carry out the low uncut chip thickness experiments in the Summer of 2004. A Toshiba Diamond Turning Lathe is available at NUS that is capable of cutting both non-ferrous and ferrous materials at nanometric depths of cut.